The Operational Performance of Hydrogen Masers in the Deep Space Network (The Performance of Laboratory Reference Frequency Standards in an Operational Environment)

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Spacecraft navigation to the outer planets (Jupiter and beyond) places very stringent demands upon the performance of frequency and time (F&T) reference standards. The Deep Space Network (DSN) makes use of hydrogen masers as an aid in meeting the routine F&T operational requirements within the 64-m antenna network. Results as of October 1980 indicate the hydrogen masers are performing within the required specifications. However, two problem areas remain that affect operations performance: (1) there is insufficient control over the environment in which the reference standards reside and, (2) frequency drift makes it very difficult to maintain the 64-m-DSS-to-64-m-DSS synt over the 130-day period required by the flight project.

I. Introduction

The "laboratory standards" are three hydrogen masers (Smithsonian Astrophysical Observatory (SAO) Model VLG10B) and six cesium oscillators (Hewlett-Packard Model 5061A-004 option). The "operational environment" is an isolated temperature controlled room at each of three NASA/JPL Deep Space Network (DSN) complexes.

This Precision Time and Time Interval (PTTI) application is in support of refined spacecraft navigation to the outer planets (Jupiter and beyond) and to provide wideband (> 100 kilobits) telecommunications channels at S- and X-band. The Voyager project Navigation team guides the spacecraft to Jupiter, Saturn, Uranus, and perhaps Neptune. The Telemetry and Image Processing teams have brought us the beautiful full-color pictures of the planets and their satellites. Last, the Radio Science team uses spectral analysis to detect and measure the constituents of planetary atmospheres, orbital rings, and gravimetrics.

II. Requirements and Specifications

Because the Voyager project requirements are currently the most stringent, they have been the dominant force in the design of the Frequency and Time System (FTS). The requirements are: (1) the fine-spectral performance of and long-term stability of the hydrogen maser, (2) the accuracy and reliability of the cesium oscillators, and (3) some means of synchronizing the intercontinental network of tracking stations.

The specifications relating to a typical frequency and timing system using hydrogen masers and cesium oscillators are listed in the Precision Time and Time Interval (PTTI) literature and manufacturers specifications, and will not be dealt with further in this article. I will instead address the very stringent requirements for syntonization and synchronization.

A. Syntonization Requirements

(1) The frequency offset between any pair of 64-m Deep Space Stations (DSS) shall be known to within less than $\pm 3 \times 10^{-13}$, such as DSS 63 (Madrid, Spain) vs DSS 43 (Canberra, Australia) = $< \pm 3 \times 10^{-13}$, or DSS 63 vs DSS 14 (Goldstone, California) = $< \pm 3 \times 10^{-13}$, or DSS 63 vs DSS 14 = $< \pm 3 \times 10^{-13}$.

(2) The frequency offset of the DSN master (DSS 14) shall be maintained within $\pm 3 \times 10^{-13}$ of Universal Time, Coordinated (UTC), kept by the National Bureau of Standards (NBS).

B. Synchronization Requirements

(1) The time offset between any pair of 64-m DSSs shall be known within ±20 μs.

(2) The time offset of any 64-m DSS from UTC shall be known within ±20 μs and, further, it shall actually be maintained to within < ±50 μs over the 130-day period August 4 through December 12, 1980.

III. Methodology

Both the synchronization (sync) and syntonization (synt) were established through use of a specially calibrated 5061A-001-004 portable unit.[1] For purposes of maintaining the individual DSS synchronization to UTC, the portable unit was carried to the host country frequency and time metrology agency. The sync/synt tool used by the San Fernando Observatory (SFO) in Spain is the Mediterranean chain LORAN-C. In Australia, the responsible agency is the Department of National Mapping and the frequency and time (F&T) maintenance resource is ABC television (see Fig. 1). In America, at Goldstone, California, regular 60-day traveling clock flights to NBS in Boulder, Colorado, and daily VLF transmissions from the NBS are used, in addition to LORAN-C and traveling clocks from other agencies (Goddard Space Flight Center and the U.S. Naval Observatory (USNO). The DSS-to-DSS synchronization and syntonization is being maintained through the use of Very Long Base Interferometry (VLBI). Some of the results are reported in Ref. 1. Figure 2 illustrates how the DSS-to-DSS and the DSN-to-UTC synchronization is maintained.

Each 64-m DSS has been delegated the responsibility of maintaining its own internal synchronization. Figure 3 illustrates the hardware configuration and data flow paths that achieve this. In addition, it is responsible for establishing and maintaining the synchronism of other DSSs within the complex (see the detail in the upper and lower right segments of Fig. 2).

IV. Test Results

A. Environmental Tests

Table 1 lists the results of environmental tests performed on five of the six 5061A cesium oscillators presently deployed within the DSN. These tests were performed at the Reference Standards Test Facility in Pasadena. Note that serial No. 1718 in its response to temperature variations differed from the others. When this unit was sent to the Goldstone Reference Standards Laboratory for zeeman calibration, it exhibited phase glitches. It was returned to Pasadena for further environmental testing.

Table 2 lists the results of environmental tests performed on the three hydrogen masers presently deployed within the DSN. Figure 4 illustrates the behavior of hydrogen-maser SAO serial No. 6 in a changing pressure environment. Note the improvement (8.2 dB) in its performance after being refurbished (Table 2, column 6).

Figure 5 illustrates the performance of SAO serial No. 7 in a changing magnetic environment. Having been given erroneous information on how far the 26-m antenna was from the planned site for the frequency standards room, it was decided that no further magnetic shielding would be required. SAO serial No. 6 failed in spring 1980 and was returned to the manufacturer for refurbishment. Table 2, column 5 indicates a 2.7-dB degradation to its performance in a changing magnetic environment.

Figure 6 illustrates the performance typical of a hydrogen maser in a high-temperature environment. The hydrogen maser is JPL serial No. 1 and the environment was an unventilated

[1] After allowing 24 hours for the portable 5061A to stabilize to its temperature and magnetic environment, the unit was degaussed and a measurement was made of the zeeman frequency vs frequency offset of the unit references to the DSN master. Using a digital frequency synthesizer and a differential voltmeter, the zeeman frequency readings were reproducible within 0.7 Hz. The portable unit was then carried to the remote DSS to be syntonized. Here again the unit was given 24 hours to stabilize, was degaussed and the zeeman frequency was measured. If the zeeman changed by more than 1.4 Hz it was reset. Otherwise a correction factor of 8.3×10^{-15}/Hz and 1×10^{-13}/°C was applied to the syntonization.

room in the cellar of DSS 43. The high temperatures caused the unit to fail in late summer (southern hemisphere). An air conditioner with 0.1°C temperature control was installed in early September 1980.

B. Stability Tests

Figure 7 illustrates the short-term stability (spectral performance) of a typical 5061A-004 cesium oscillator and a typical hydrogen maser. These measurements were made in Spain at DSS 63 where the Complex Maintenance Facility (CMF) was close enough to permit use of a coaxial cable from the hydrogen maser. Cesium oscillator serial No. 1511 was the portable unit and it was carried to the CMF facility.

Figures 8a and 8b (from Ref. 2) give the stability performance characteristics of the three hydrogen masers presently deployed. Figure 9 illustrates the stability characteristics of a recent series (serial Nos. 1718 and 1719) of 5061A-004 cesium oscillators.

V. Synchronization and Syntonization Data

A. Epoch Synchronization

Prior to departure for the trip to Spain, the portable clock designated RSL-2 was used to synchronize itself and the DSN master clock at DSS 14 to within 0.2 μs of the NBS and USNO epoch. It was then transported to DSS 63 at Robledo, Spain, then on to the SFO at San Fernando, Spain. One day prior to leaving Spain, the clock was transported to DSS 62 at Cebreos and the Madrid STDN station. Thus the three stations in the Madrid complex were synchronized to SFO and the DSN master to less than one μs.

Upon returning to America, the clock was immediately taken to Goldstone for closure against the DSN master. It then was taken to Australia where it was used to synchronize DSS 43 at Tidbinbilla, and then to the Department of National Mapping (DNM) installation in the Orroral Valley. On the day prior to leaving Australia, the portable clock was used to synchronize DSS 44 (Honeysuckle Creek) and Orroral (the STDN station) to the DNM, DSS 43, and the DSN.

The RSL-2 was then returned to America where closure was refined against both NBS and USNO. All the elements and agencies synchronized on these trips remain synchronized to within less than 1 μs, and are being maintained within 10 μs peak to peak.

B. Syntonization[2]

Each time the calibration process was performed, 24 hours was allowed for thermal stabilization and then 80 hours (ten 8-hour samples) of comparative phase data were collected. This was performed with instrumentation configured as that in Figure 3, except that a fourth phase comparator was added to permit the intercomparison of the hydrogen maser, cesium oscillator Nos. 1 and 2, and the portable cesium oscillator (RSL-2).

At DSS 63, after settling from the trauma of the trip and after thermal stabilization, the zeeman frequency of RSL-2 had shifted but 1.7 Hz. A C-field adjustment removed approximately one-half of the zeeman offset and the calibration process of the hydrogen maser began. At the end of the 88-hour calibration period, the hydrogen maser frequency offset from the DSN master was found to be zero $\pm 5 \times 10^{-14}$ instrumentation noise. It was thus unnecessary to make any adjustment to the hydrogen maser. It was, however, necessary to adjust both cesium oscillator Nos. 1 and 2. Data collected via LORAN-C indicate the frequency offset of the hydrogen maser and cesium oscillator No. 2 remain at zero $\pm 4.8 \times 10^{-13}$ as of November 8, 1980.

At DSS 43, the thermal stabilization period was extended to allow for the lack of good circulation (the air-handler installation was still in process). Also, the hydrogen maser had been installed just a few weeks and was still drifting. At the end of an 80-hour calibration period, the offset of the maser from the DSN master was 4.73×10^{-13}. Since this was beyond the Voyager specification, and since the drift was in a positive direction, the hydrogen maser synthesizer was reset to reduce its frequency by 6.345×10^{-13}. Frequency offset data of this maser vs UTC (Australia) (AUS) collected using simultaneous TV with the DNM indicate its drift has cancelled the value reset on September 30. Close examination of recent data indicate the second-order drift term has dropped from 4.6×10^{-14}/day to 2.1×10^{-14} to 0.7×10^{-14}/day.

All indications are that the frequency drift of SAO No. 5, the DSN master, has dropped well below its former value of 1×10^{-14}/day as observed between the departure for Spain and the return for closure. At present, SAO No. 5 vs UTC (NBS) = $-2.84 \times 10^{-13} \pm 0.3$ as verified by two closures against UTC(NBS) within a 21-day period. Figure 10 gives time offset data vs UTC(DSN) and associated frequency offset data for each of three 64-m DSSs. Figure 11 gives time offset data vs UTC(NBS and USNO) and the associated frequency offset data vs UTC(NBS) of the DSN master reference.

[2]Events occurring subsequent to the end of the Voyager 1 encounter period have provided additional performance data (see Appendix).

VI. Summary

(1) Hydrogen masers require 4 to 6 weeks of thermal stabilization before their long-term stability can be fully utilized.

(2) To use the full potential of present day hydrogen masers and cesium reference frequency standards, care must be exercised to provide a thermally stabilized and magnetically isolated environment.

(3) Syntonization to UTC can be accurately and economically maintained within a part in 10^{13} (after 1 week of daily observations) through use of the simultaneous reception of LORAN-C or TV transmissions by the DSS and the host country frequency and time metrology service agency.

References

1. Madrid, G. A., et al., "Short Turn-Around Intercontinental Clock Synchronization Using Very Long Baseline Interferometry – A Progress Report," in *Proceedings of the 12th Annual Precise Time and Time Interval Applications and Planning Meeting*, pp. 445-449. Goddard Spaceflight Center, Greenbelt, Md.

2. Kuhnle, P. F., "Hydrogen Maser Implementation in the Deep Space Network at the Jet Propulsion Laboratory," in *Proceedings of the 11th Annual Precise Time and Time Interval Applications and Planning Meeting*, November 27, 1979. Goddard Spaceflight Center, Greenbelt, Md.

3. U.S. Naval Observatory, *Report of Precise Time Measurement* 1/14/81 FTS 411 clock located DSSs 61 and 63, Madrid, Spain. Date and time of measurement: 1980 Dec. 11, 1450 UT, MJD 44584 measurement UTC(USNO MC)-UTC(FTS 411) = 0.8 ±0.2 μs.

4. U.S. Naval Observatory, *Report of Precise Time Measurement* 2/10/81 STA/HYM2 located DSSs 42 and 43, Tidbinbilla, Australia. Date and time of measurement: 1981 Jan. 6, 0026 UT, MJD 44610 measurement UTC(USNO MC)-UTC(STA HYM2) = 1.7 ± 0.2 μs.

Table 1. Cesium oscillator environmental parameters test data

Parameter	Hewlett-Packard 5061-A 004 No. 1694	No. 1695	No. 1717	No. 1718	No. 1719
Temperature, $\frac{\Delta F}{F}$/°C	4.3×10^{-14}	6.25×10^{-14}	5.4×10^{-14}	1.2×10^{-13} to -2×10^{-13}	5.6×10^{-14}
Barometric pressure, $\frac{\Delta F}{F}$/in. Hg	1×10^{-13}	1×10^{-13}	1×10^{-13}	1×10^{-13}	1×10^{-13}
Magnetic field,[a] $\Delta F/F/10^4$ Wb/m^2	1×10^{-13}	1×10^{-13}	1×10^{-13}	1×10^{-13}	1×10^{-13}

[a]1 gauss = 10^4 Wb/m^2

Table 2. Hydrogen-maser environmental parameters test data

Parameter	SAO 5	SAO 6	SAO 7	SAO 5 (After refurbishment by mfr.)	SAO 6 (After refurbishment by mfr.)
Temperature, $\frac{\Delta F}{F}$/°C	-1.6×10^{-14}	-1×10^{-13}	7.0×10^{-14}	-1.2×10^{-13}	7.2×10^{-14}
Barometric pressure, $\frac{\Delta F}{F}$/in. Hg	2.6×10^{-14}	-3.4×10^{-13}	2.3×10^{-14}	2.5×10^{-14}	-5.1×10^{-14}
Magnetic Field,[a] $\Delta F/F/10^4$ Wb/m^2	1.6×10^{-12}	5.0×10^{-12}	2.8×10^{-12}	3.0×10^{-12}	3.4×10^{-12}

[a]1 gauss = 10^4 Wb/m^2

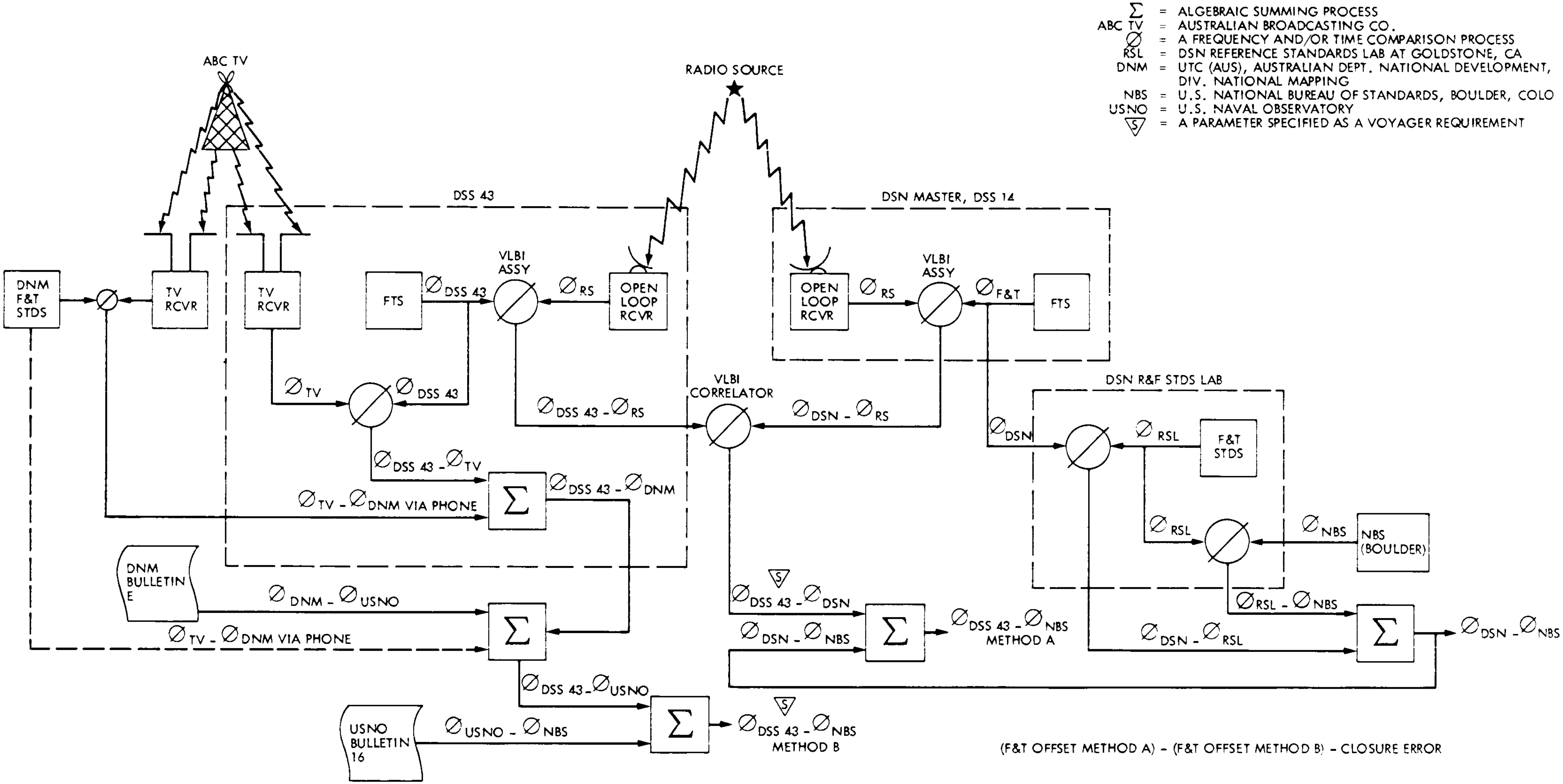

Fig. 1. UTC (DSN) – UTC (NBS) vs UTC (DSN) – UTC (USNO) via UTC (Australia)

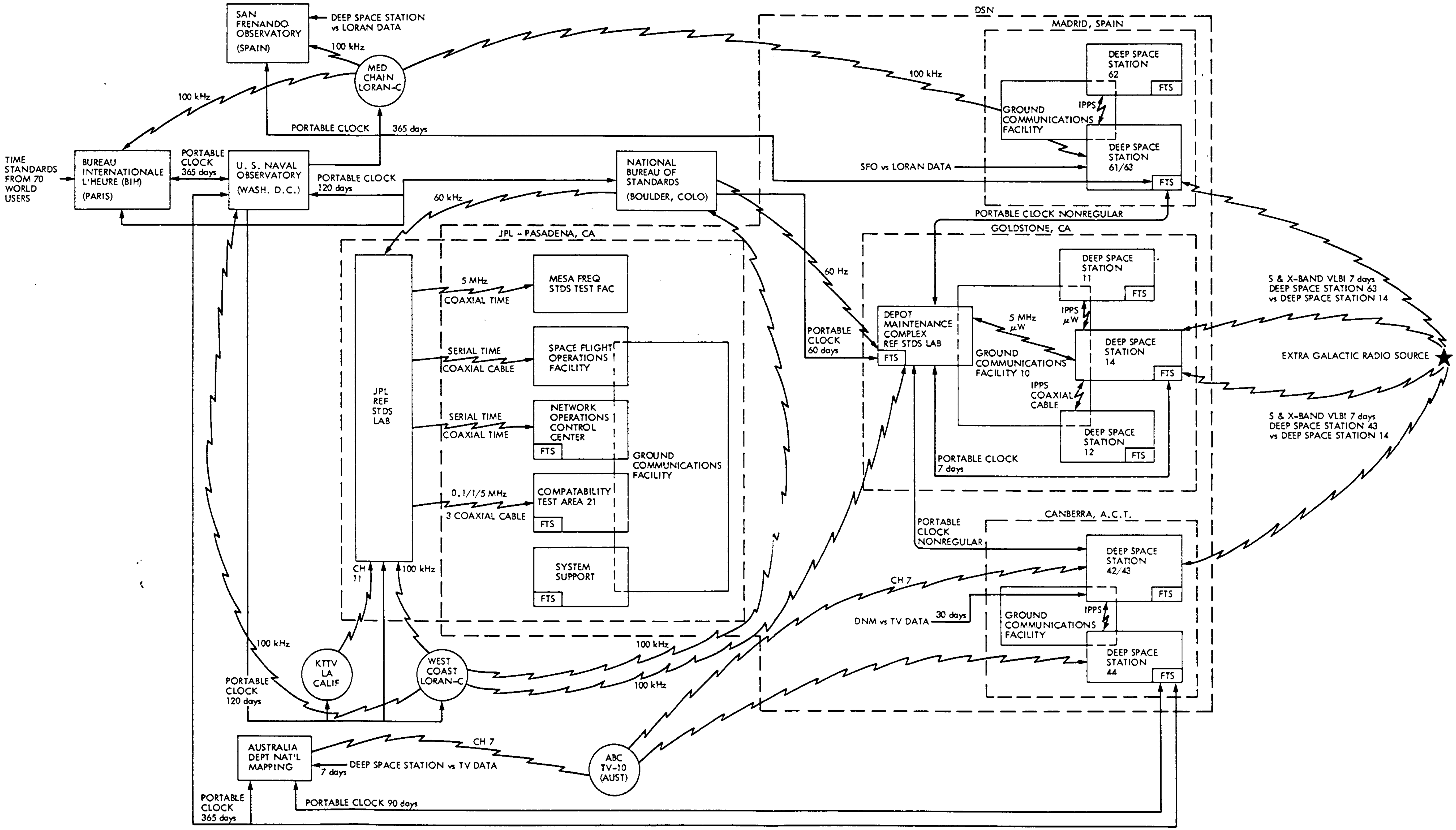

Fig. 2. NASA/JPL Intra/Extra DSN Frequency and Time Sync System

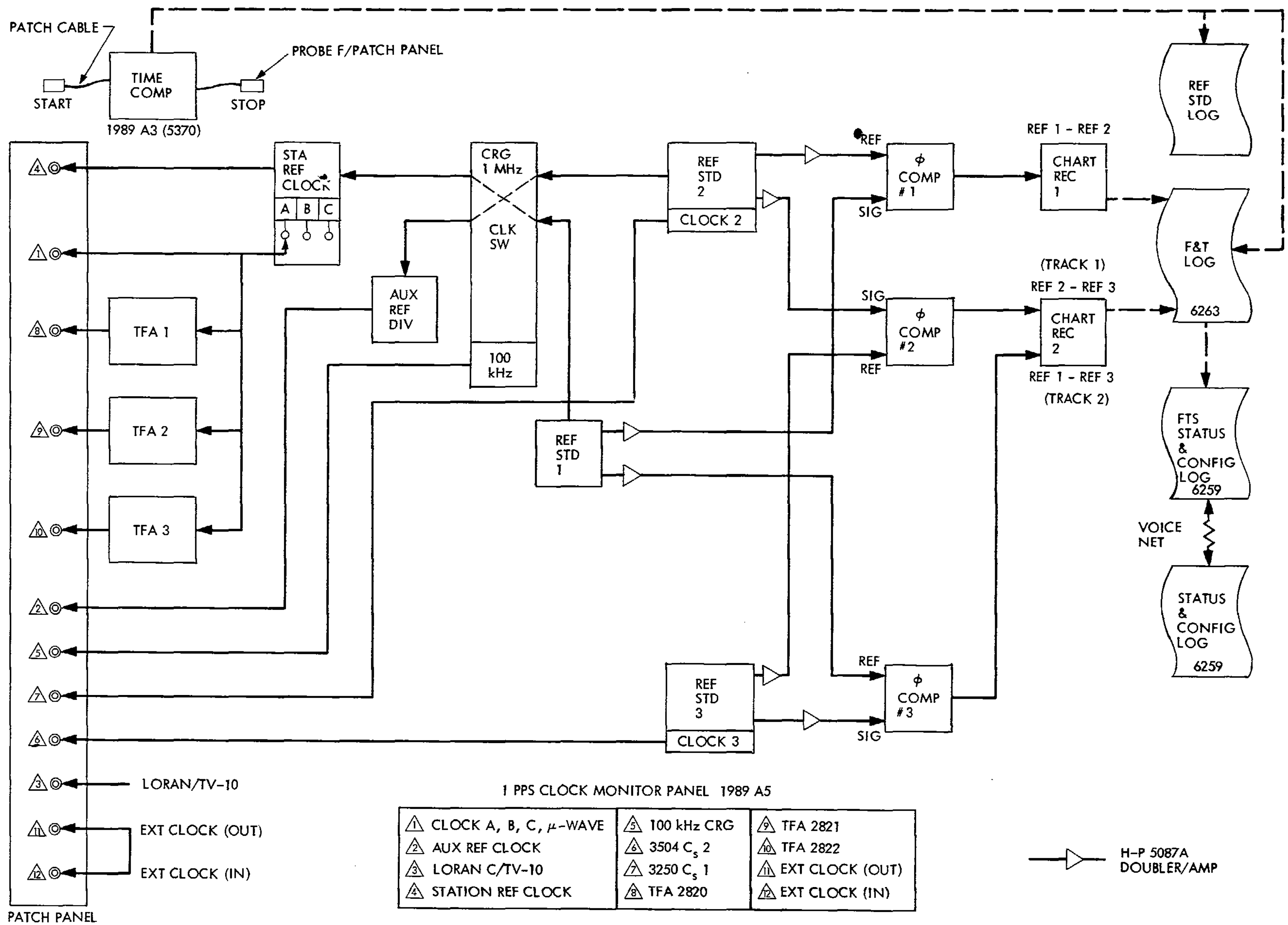

Fig. 3. Frequency and time monitoring at 64-meter DSS

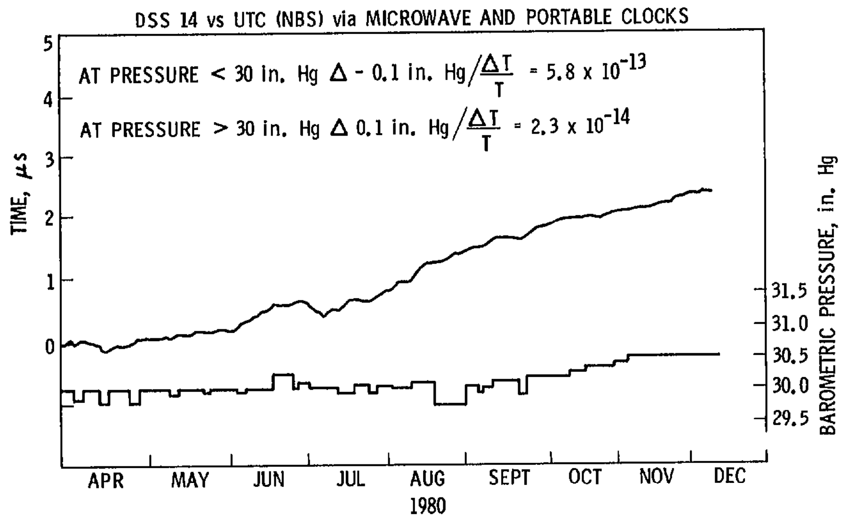

Fig. 4. Hydrogen-maser performance in a changing barometric pressure environment

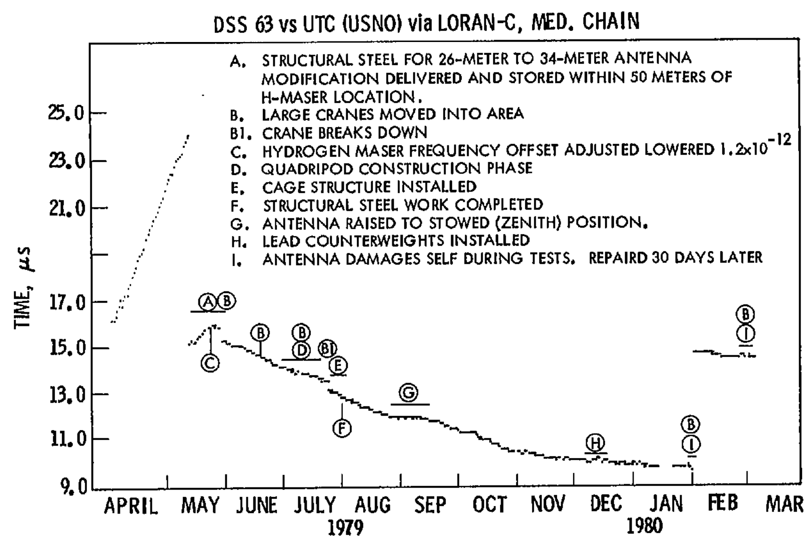

Fig. 5. Hydrogen-maser performance in a changing magnetic environment

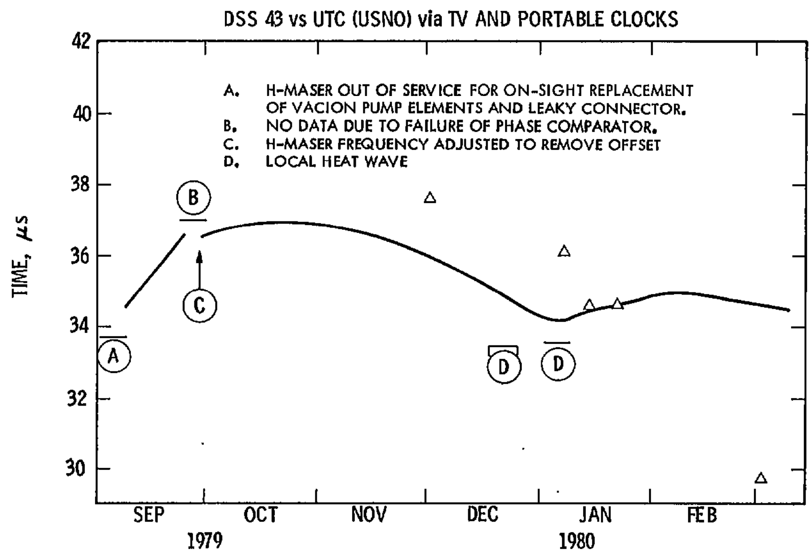

Fig. 6. Maser performance in a changing temperature environment

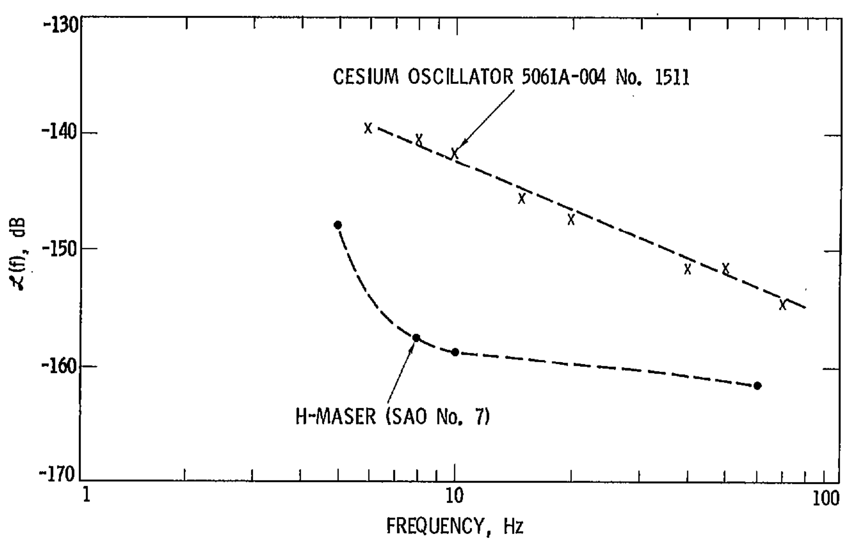

Fig. 7. Reference standards spectral performance (f) vs frequency

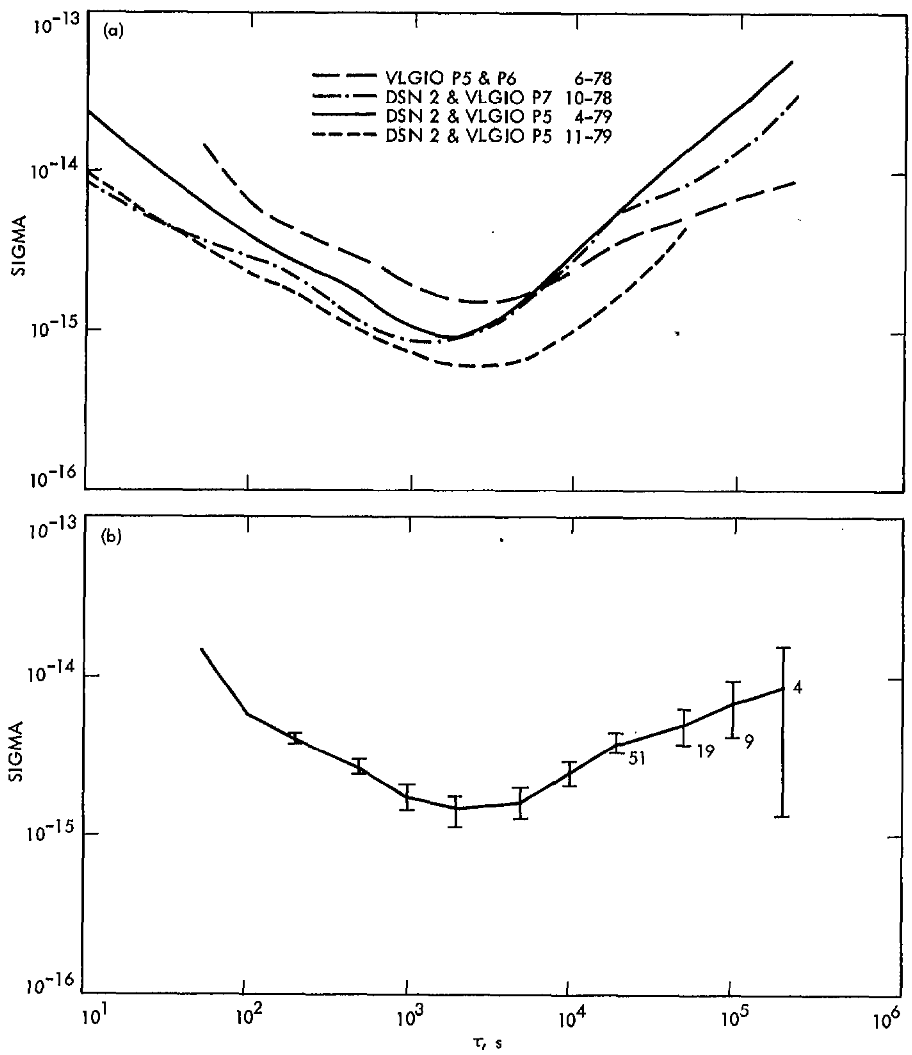

Fig. 8. Allan variance (a) vs sampling time, (b) vs sampling time with error bars

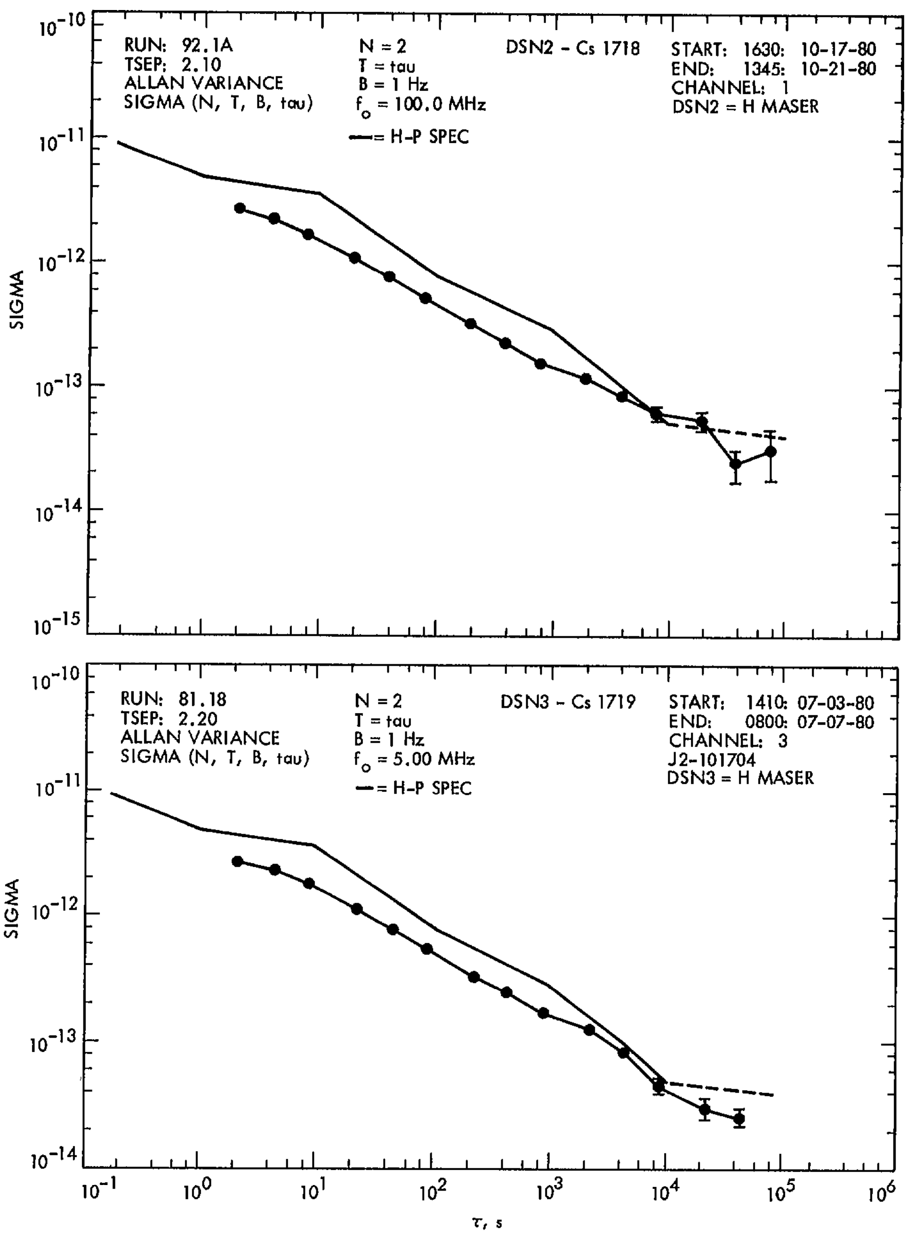

Fig. 9. Stability test data

FTS Quicklook Data

DOY	DSS-14 T.O. (μs)	DSS-14 Rel. Rate (μs/μs)	DSS-42/43 T.O. (μs)	DSS-42/43 Rel. Rate (μs/μs)	DSS-61/63 T.O. (μs)	DSS-61/63 Rel. Rate (μs/μs)
286	0.00	—	-2.70	—	2.3	—
287	0.00	0.0	-2.70	0.0	2.3	0.0
288	—	—	-2.67	3.47 (-13)	2.2	-1.16 (-12)
289	0.00	—	-2.63	4.63 (-13)	2.3	1.16 (-12)
290	0.80	9.26 (-12)	-2.60	3.47 (-13)	2.3	0.0
291	0.80	0.0	-2.56	4.63 (-13)	2.2	-1.16 (-12)
292	0.80	0.0	-2.52	4.63 (-13)	2.2	0.0
293	1.00	2.31 (-12)	-2.49	3.47 (-13)	2.3	1.16 (-12)
294	0.80	-2.31 (-12)	-2.44	5.79 (-13)	2.4	1.16 (-12)
295	1.20	4.62 (-12)	-2.41	3.47 (-13)	2.4	0.0
296	0.80	-4.62 (-12)	-2.38	3.47 (-13)	2.3	-1.16 (-12)
297	0.80	0.0	-2.34	4.63 (-13)	2.3	0.0
298	-0.30	-1.27 (-11)	-2.31	3.47 (-13)	2.4	1.16 (-12)
299	-0.30	0.0	-2.27	4.63 (-13)	2.4	0.0
300	-0.20	1.16 (-12)	-2.24	3.47 (-13)	2.5	1.16 (-12)
301	-0.30	1.16 (-12)	-2.20	4.63 (-13)	2.4	1.16 (-12)
302	-0.28	2.31 (-13)	-2.17	3.47 (-13)	2.4	0.0
303	-0.30	-2.31 (-13)	-2.13	4.63 (-13)	2.4	0.0
304	-0.30	0.0	-2.10	3.47 (-13)	2.3	1.16 (-12)
305	-0.35	-5.79 (-13)	-2.06	4.63 (-13)	2.3	0.0
306	-0.40	-5.79 (-13)	-2.03	3.47 (-13)	2.3	0.0
307	-0.30	1.16 (-12)	-2.00	3.47 (-13)	2.3	0.0

Considering weekly segments:

Over	$T_e - T_s$	Rel. Rate	$T_e - T_s$	Rel. Rate	$T_e - T_s$	Rel. Rate
286-293	1.00	1.45 (-12)	0.21	3.04 (-13)	0.0	0.0
293-300	-1.20	1.74 (-12)	0.25	3.62 (-13)	0.20	2.89 (-13)
300-307	-0.10	1.45 (-13)	0.24	3.47 (-13)	-0.20	-2.89 (-13)

Fig. 10. 64-meter DSS F & T offset report

DE JGLD 014
12/1714Z
FM W WOOD/JW MYERS
TO JJPL/S WARD/J LUVALLE/J MANKINS
INFO JJPL/R COFFIN/R LATHAM/T TAYLOR
JHIL/K BEUTLER/J C LAW
JZED/NET ANALYSIS
DLD/R RUXLOW/B MCPARTLAND/J MCCOY

SUBJECT: UTC(RSL) – UTC(NBS) EPOCH TIME SYNCHRONIZATION.

TWO PORTABLE CLOCK TRIPS TO BOULDER, COLO. IN OCTOBER ALLOWED US TO REFINE THE ESTIMATE OF OUR TIME AND FREQUENCY OFFSETS TO NBS, USNO, AND B.I.H.

1. PUBLISHED DATA, AND DERIVATIONS BASED ON PUBLISHED DATA:
(NBS TIME & FREQUENCY BULLETIN 274, USNO SERIES 7-669)
UTC(USNO) – BIH = -0.694 X 10 -13
UTC(USNO) – UTC(NBS) = -0.9513 X 10 -13
TA NBS – UTC(NBS) = -0/0143 X 10 -13
TA NBS – BIH = +0.243 X 10 -13 (+/- 0.279 X 10 -13)

2. RESULTS OF MEASURED DATA:

	DAY 281	DAY 302	ΔF/F ηs/DAY
RSL2-UTC(RSL) =	-0.244 μS	+0/182 μS	
RSL2-UTC(NBS) =	+0.103 μS	+0.349 μS	
UTC(RSL)-UTC(NBS) =	+0.347 μS	+0.166 μS	-8.658
UTC(RSL)-UTC(USNO) =	+0.788 μS	+0.799 μS	-0.431
CS1 14-UTC(NBS) =	+0.487 μS	+0.374 μS	-5.2546
CS1 14-UTC(USNO) =	+0.928 μS	+0.987 μS	+2.7656
CLOCK 'A' 14-UTC(NBS) =	+2.168 μS	+1.641 μS	-24.574
CLOCK 'S' 14-UTC(USNO) =	+2.609 μS	+1.995 μS	-16.326
H2M14-UTC(NBS) =	NA	NA	-26.604
H2M14-UTC(USNO) =	NA	NA	-18.384

NOTE: THE H2M(14) FREQUENCY OFFSET IS TAKEN FROM THE PHASE RECORDER COMPARISON TO CS1 14, AND IS OVER THE SAME PERIOD AS THE CLOCK CLOSURES TO NBS. NOTE ALSO THAT CLOCK 'A' 14 (DRIVEN BY THE H2M) IS PROBABLY A MORE PRECISE ESTIMATE OF THE H2M POSITION.

REGARDS

Fig. 11. DSN master frequency and time report

Appendix

The following covers events relating to hydrogen maser performance history and the long-term stability performance of the two overseas units. The closure data resulting from the USNO traveling clock measurements (Refs. 3 and 4) provided the most accurate means of validating the frequency offset performance data.

(1) On day 319 (November 14, 1980), the hydrogen maser (H_2M), SAO-VLG-10 Serial No. 7, located at DSS 63 failed. This outage was caused by failure of the VACION pump assembly.

(2) On day 346 (December 11, 1980), a traveling clock, traceable to UTC (USNO), visit was made to DSS 63. Data from this Report of Precise Time Measurement (Ref. 3) has produced the following results:

(a) The DSS 63 on-line reference frequency standard was 5.9×10^{-13} (51 ns/day) faster than the UTC (USNO) rate over the 88-day period (September 15 through December 11, 1980). The uncertainty on this measurement was $\pm 4 \times 10^{-14}$ (± 3.2 ns/day).

(b) Using daily time offset measurements referenced to Mediterranean Chain LORAN-C, DSS 63 personnel were able to maintain knowledge of the reference frequency standard's frequency offset to within $\pm 4.1 \times 10^{-13}$ of the UTC (USNO) rate. Noise on the LORAN-C receptions over this 88-day data span introduces an error > 90%.

(c) The drift in the output frequency of the H_2M SAO VLG-10 Serial No. 7 is less than 6.5×10^{-14} per day. This measurement, however, is seriously limited by instrumentation errors of >70%, and it includes the noise introduced by operator technique.

(3) On day 006, 1981, a traveling clock, traceable to UTC (USNO), visit was made to DSS 43. Data from this Report of Precise Time Measurement (Ref. 4) has produced the following results.

(a) The DSS 43 on-line reference frequency standard was 8.1×10^{-14} (7 ns/day) slower than the UTC (USNO) rate over the 100-day period (September 30, 1980, through January 6, 1981). The uncertainty on this measurement was $\pm 3 \times 10^{-14}$.

(b) Using daily time offset measurements referenced to UTC (Australia) through the medium of public television broadcasts (Fig. 1, Method B), DSS 43 personnel were able to maintain knowledge of the reference standard's frequency offset to within $\pm 2.3 \times 10^{-14}$ of the UTC (USNO) rate. Noise on the TV receptions over this 100-day data span introduced an error of <10%.

(c) The drift in the output frequency of H_2M SAO VLG-10 Serial No. 6 is $<5.7 \times 10^{-14}$ per day. Again, the limitation on the accuracy of this measurement is instrumentation/technique errors (40%).

Summary: The performance of both the overseas hydrogen masers was within all Voyager Project specifications for Encounter No. 1. However, validation of this at DSS 63 was not possible without the second traveling clock visit, due to insufficient instrumentation precision.